Pulsar wind nebulae around the southern pulsars PSR B1643−43 and PSR B1706−44

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ABSTRACT

We present high resolution VLA images taken at the wavelengths of λ20 cm, λ6 cm, and λ3.6 cm in the vicinity of the pulsars PSR B1706−44 (PSR J1709−4428) and PSR B1643−43 (PSR J1646-4346). Both of these pulsars are young (<30,000 yrs) and have large spin-down luminosities ($\dot{\mathrm{E}}> 10^{35}$ ergs^{-1}) and hence are good candidates to search for extended synchrotron nebula excited by the relativistic pulsar wind. For PSR B1643−43 we found evidences of a $4'$ comet-shaped nebula, suggestive of a synchrotron "wake" left by a fast moving pulsar. PSR B1706−44 appears surrounded by a spherical nebula approximately $3'$ in diameter. Based on their morphology, the detection of significant linear polarization (>20%), and their flat radio spectra ($\alpha = 0.25 - 0.3$, where $\mathrm{S}_\nu \propto \nu^{-\alpha}$) we argue that these are wind nebulae powered by the rotational energy loss of the respective pulsars.

Subject headings: ISM: general – supernova remnants – pulsars: individual (PSR B1643−43) (PSR1706−44)

1. Introduction

Pulsars transfer the bulk of their rotational angular momentum in a wind of relativistic particles and Poynting flux (Michel 1969, Rees & Gunn 1974, Kennel et al. 1983). However, because the particles emerge from the magnetosphere with zero pitch angle, the winds cannot be directly observed. Therefore in order to study the winds from pulsars it is necessary to study the synchrotron emission from the pulsar wind nebula (PWN) produced when the wind is thermalized as it comes into pressure equilibrium with the surroundings. The Crab nebula is the archetype of the PWN; this source has been studied in detail at all wavelengths (e.g. X-ray: Brinkmann, Aschenbach & Langmeier 1985, radio: Bietenholz & Kronberg 1992, optical: Hester et al. 1995). The fact that the bolometric luminosity of the Crab nebula requires an on-going source with a power comparable to the rotational energy loss ($\dot{\mathrm{E}}$) of the pulsar, shows that the PWN owes its existence to the existence of a young, energetic pulsar.

At radio wavelengths, there are at least two morphological types of PWN, depending on the source of confinement for the wind (Frail & Scharringhausen 1997, Chevalier 1998, Gaensler et al. 2000): the so called "filled-center" and the "bow-shock". The filled-center PWN or "plerions" (e.g. Crab) are inside young supernova remnants and are confined by the hot gas driving the expansion. The bow-shock PWN are found both inside and outside supernova remnants (e.g. PSR B1757−24 and G5.4−1.2; Frail & Kulkarni 1991) and are confined by the high space velocities of the pulsar. The non-thermal radio emission from PWN can be distinguished from shock-accelerated emission in supernova remnants by (1) a flat spectrum, $\alpha = 0.1$ to 0.3, where $\mathrm{S}_\nu \propto \nu^{-\alpha}$, and (2) a high degree of linear polarization ($>> 5\%$) (Chevalier 1998).

The existing sample of radio PWN is small. There are no more than seven confirmed PWN at radio wavelengths (the number is comparable for X-ray PWN) which contain a known pulsar. Frail, Goss & Whiteoak (1994) (hereafter FGW94) made radio images around three young pulsars, and identified two promising PWN candidates based on their morphology alone. In this paper we present multi-frequency polarimetric observations made with the National Radio Astronomy Observatory (NRAO[2]) Very Large Array (VLA) toward PSR B1643−43 and PSR B1706−44 to better ascertain the properties of the emission in the vicinity of these pulsars.

2. Observations

The extended emission in the vicinity of PSR B1643−43 and PSR B1706−44 was imaged at 1425, 4860 and 8460 MHz in several observing runs during 1997, using different configurations of the VLA (see Table 1). The data were obtained in the Stokes parameters I, Q, U, and V. The *uv* data from each array were combined to form a single dataset for each pulsar in order to image a full range of spatial frequencies. An additional 1.4 GHz dataset, taken in 1993 with the VLA in its CnB and DnC hybrid configurations, was extracted from the archive. A description of these data can be found in FGW94. All data reduction and calibration were done following standard practice in use at the VLA. The images were corrected for primary beam. Table 1 summarizes the observational parameters.

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3. Results

3.1. PSR B1643−43

PSR B1643−43 (PSR J1646-4346) is a 232 ms pulsar, with a characteristic age of 32.6×10^3 yr, a spin-down luminosity 3.6 $\times10^{35}$ erg s^{-1} (Johnston et al. 1995) and a dispersion measure-based distance of 6.9 kpc (Taylor & Cordes 1993). A search for pulsed γ-ray emission was made with the EGRET and COMPTEL instruments on board of the Compton Gamma-Ray Observatory with null results (Thompson et al. 1994, Carramiñana et al. 1995).

Based on observations carried out with the VLA in the radio continuum at λ20 cm in an extended region around PSR B1643−43, FGW94 have shown that the pulsar is located within the shell of the SNR G341.2+0.9, about $8'$ west of the center of the remnant (see Fig.1 *Left*). Morphological evidence and a coincidence in distance led FGW94 to propose a physical association between the pulsar and the remnant. FWG94 have also reported the detection of a $4'$ nebulosity with a cometary morphology just east of PSR B1643−43 which is joined to the pulsar by a bridge of emission. Based on morphological evidence the authors suggested that this feature is the synchrotron nebula left behind by the fast moving pulsar. The characteristic age of PSR B1643-43 and its positional offset from the center of G341.2+0.9 together imply a transverse velocity of 475 km s^{-1}, which in the absence of proper motion measurements predicts that the pulsar would have to be moving about 15 mas yr^{-1} (FGW94).

In the same survey, FWG94 noted that the position of PSR B1643−43 most likely coincided with a 1.5 mJy point source detected in their λ20 cm VLA radio image. Their interferometric position differed significantly ($40''$) from the timing position of the pulsar (Johnston et al. 1995). The later is probably an error due to the timing noise and "glitches" that characterize the spindown of young pulsars. The present observations, performed with better sensitivity and spatial resolution than in FGW94, allow us to derive an improved interferometric position for the pulsar. Our best position determination is from the BnA array λ20 cm data with a beamwidth of $7''.3 \times 3''.7$, a considerable improvement over the $25''$ beam in FGW94. A fit to the peak gives a position (epoch B1950) of R.A.= $16^h43^m16^s.56 \pm 0^s.04$, decl.=$-43°40'31''.8 \pm 0''.8$, or (epoch J2000) R.A.=$16^h46^m50^s.86 \pm 0^s.04$, decl.=$-43°45'53''.7 \pm 0''.8$. We have also determined the position of the pulsar using each dataset separately and at all frequencies and find good agreement. The derived position is about $5''$ northwest of the position given by FWG94. We suspect that extended nebular emission underlying the pulsar is shifting the centroid and therefore the present position with its much smaller beam is superior to the that of FGW94.

Figure 1 (*Right*) shows a grayscale and countour images of a region surrounding PSR 1643−43 at 1.4 and 4.8 GHz. These images were convolved to a $25''$ circular beam. The cross indicates the new position of the pulsar. Because of the incomplete sampling of the visibility plane, the VLA image at 8.4 GHz lacks short spacings and is not included here.

From Figure 1 (*Right*) a synchrotron nebula of about $3'$ in size is clearly visible. The nebula, with the pulsar located at its western border, appears as a feature pointing back from the pulsar to the center of G341.2+0.9 in the direction opposite the pulsar's implied proper motion. Such a morphology is compatible with the interpretation of this structure as a PWN. Similar radio morphologies have been detected before surrounding PSR B1757-24 in the SNR G5.4−1.2 (Frail & Kulkarni 1991), and PSR B1853+01 in W44 (Frail et al. 1996).

We find additional evidence to support our contention that this feature is the PWN associated with PSR B1643−43. i) We detect significant linearly polarized intensity at 4.8

and 8.4 GHz, with a mean fractional polarization of about 30%. ii.) We also estimated the total flux density for the nebular emission (and for the pulsar). These values are given in Table 2. The errors quoted include the rms noise of each image and the uncertainty in the choice of the integration boundaries. From a least squares fit we derive a radio spectral index $\alpha = 0.24$ between 330 MHz and 4.8 GHz, where the data at 330 MHz were taken from FWG94 and data at 843 MHz were taken from the MOST survey by Green et al. (1999). A high degree of linear polarization and a flat radio spectral index are two unmistakable properties of PWN in the radio band, and thus we propose that this is the synchrotron nebula excited by the pulsar wind.

For a distance of 6.9 kpc, the corresponding radio luminosity L_r of the PWN between 10^7 and 10^{11} Hz is 8.3 $\times 10^{31}$ erg s^{-1}. This value corresponds to an efficiency $\epsilon \equiv L_r/\dot{E} =$ 1.6 $\times 10^{-4}$, in very good agreement with the $\epsilon \sim 10^{-4}$ derived by Gaensler et al. (2000) for young energetic pulsars.

3.2. PSR B1706−44

PSR B1706−44 (PSR J1709−4428) is a young pulsar (spin-down age $\sim$ 17000 yrs), with a period of 102 ms and a large spin-down luminosity of 3.4×10^{36} ergs^{-1}. It is also one of a very small number (6) of radio pulsars to have been detected as a pulsed gamma-ray source (Thompson et al. 1992). There are several lines of evidence that suggest the existence of a filled-center nebula surrounding the pulsar. FGW94 have noted in a low resolution ($24''$) radio image at λ20 cm that PSR B1706−44 appears embedded in a “halo” about $4'$ in size . The authors suggest that the emission could be due to a PWN around the pulsar. In the soft X-ray band, between 0.1-2.4 keV, unpulsed radiation was detected, with a 2 σ upper limit on the pulsed fraction of the 18 %. This unpulsed emission is thought to originate from a compact synchrotron nebula of about $1'$ in size around the pulsar (Becker et al. 1995, Finley et al. 1998). More recent X-ray observations made with *ROSAT*, *ASCA* (Finley et al. 1998) and *RXTE* (Ray et al. 1998) confirm the lack of pulsations. Observations of PSR B1706−44 in the very high energy γ rays by the CANGAROO imaging Cerenkov telescope have revealed unpulsed TeV radiation at a 10 σ confidence level (Kifune et al. 1995). It was suggested that the TeV emission could be due to inverse Compton radiation from a PWN (Harding 1996, Aharonian et al. 1997). Chakrabarty & Kaspi (1998) have reported negative results of a search for optical pulsations from PSR B1706−44. Sefako et al. (2000) have carried out V band CCD observations in the direction of the pulsar in order to look for the optical counterpart of the $1'$ compact X-ray nebula, but their search did not reveal any nebular structure around the pulsar.

A possible association between the supernova remnant (SNR) G343.1-2.3 and PSR B1706−44 was proposed by McAdam et al. (1993). Such an association, however, was questioned by FGW94 and Nicastro, Johnston & Koribalski (1996) based on distance inconsistences, a lack of morphological signatures of interaction between the pulsar and the SNR, and scintillation measurements indicating a transverse velocity for the pulsar at least 20 times smaller than required if the pulsar originated in the geometrical center of G343.1-2.3, 17000 years ago.

A dispersion based distance measure of Taylor & Cordes (1993) places PSR B1706−44 at 1.8 kpc; while HI absorption shows that its distance lies in the range 2.4-3.2 kpc (Koribalski et al. 1995). In what follows we will adopt a distance to the pulsar of 2 kpc.

As in the previous case for PSR B1643−43, we have determined the position of the pulsar using all data sets separately. Here again, the most accurate fit was obtained from the high angular resolution of the BnA array λ20 cm array data (beamwidth $9''.1 \times 4''.8$). The derived position is (epoch B1950) R.A.= $17^h 6^m 5^s.09 \pm 0^s.02$, decl.=$-44°25'20''.6 \pm 0''.5$, or (epoch J2000) R.A.=$17^h 9^m 42^s.75 \pm 0^s.02$, decl.=$-44°29'6''.6 \pm 0''.5$. This position is in good agreement with the interferometric measurements of FGW94 and the new timing position by Wang et al. (2000).

Figure 2 shows greyscale and contour images of the region surrounding the pulsar at 1425, 4860 and 8640 MHz. These images were convolved with a circular beam of $25''$. The cross indicates the position of PSR B1706−44. The pulsar appears surrounded by a synchrotron nebula, about 3'.5× 2'.5 in size, with the brightest part towards the east.

The total flux density of the nebular emission and PSR B1706−44 is summarized in Table 2. Again, the quoted errors take into account uncertainties in the definition of the outer boundaries. From a least squares fit we derive a radio spectral index $\alpha = 0.3$ between 330 MHz and 8.4 GHz, where the data at 330 MHz were taken from FWG94. Significant linearly polarized intensity was detected at 4.8 and 8.4 GHz, with a mean fractional polarization of about 20 %. This is convincing evidence that we have detected another PWN.

The radio luminosity L_r of the PWN between 10^7 and 10^{11} Hz is: 7.6×10^{30} ergs^{-1}, corresponding to an efficiency $\epsilon \equiv L_r/\dot{E} \approx 2\times10^{-6}$. These values are significantly lower than for any other radio PWN (Frail & Scharringhausen 1997). The equipartition magnetic field in the nebula can be estimated by the usual means (Pacholczyk 1970), assuming that the energy density of the magnetic field is half of the total synchrotron pressure. For an electron/positron plasma with unity volume filling factor we find $B_{eq} = 20$ μG and a minimum energy of 3×10^{45} erg.

In order to match the observed X-ray and γ-ray fluxes in PSR B1706−44, Harding (1996) proposed a scenario where the TeV emission is produced within the synchrotron nebula via the IC mechanism and the target photon field is the 2.7 K microwave background radiation (MBR). The author abtains a good fit if the magnetic field strength inside the nebula is lower than 5 μG, value lower than our estimation.

On the other hand, Aharonian et al. (1997) proposed that the production of TeV γ-rays take place in a region of about $0.1°$, outside of the compact X-ray nebula. Inside the compact nebula, where synchrotron is the dominant process, the magnetic field takes values between 20 to 60 μG (depending on the model parameters); out of this region, where the MBR photons are accelerated to TeV energy by the IC mechanism, the value of the magnetic field is about 3 μG.

Our estimate of the magnetic field in the radio nebula is in good agreement with that of the Aharonian et al's model for the compact X-ray nebula. However, this new radio observations indicate that the synchrotron nebula extends up to 3'.5. The γ photons would therefore need to be produced even farther out.

Finley et al. (1998) have also explained the unpulsed TeV emission in PSR B1706−44 as originated by the IC mechanism but in their model, the target photon field is the infrared background radiation. Their results are consistent with a continuous unbroken power-law spectrum extending from radio to X-ray domain. However, the curent radio data argue against this model. Our observations allow to better define the radio spectrum producing an $\alpha \simeq 0.3$, which when combined with that obtained from the X-ray observations implies the existence of at least one break in the synchrotron spectrum between the radio and X-ray bands.

4. Conclusions

We have made radio observations toward PSR B1643−43 and PSR B1706−44 and found good evidences that these pulsars are surrounded by extended emission, powered by their winds. At the time of the survey of Frail & Scharringhausen (1997) only six PWN were known. This present work and Gaensler et al. (1998) has extended this sample by 50%.

These new radio PWN have the same properties of the rest of the sample (i.e. morphology, spectra, polarization) as a whole with one exception. Most radio PWN radiate of order 10^{-4} of their spindown luminosity but there are a large number of non-detections (Gaensler et al. 2000) suggesting that this ratio is not constant and may be in fact much lower in specific cases. PSR B1706−44 and PSR B0906−49 both have a PWN with ϵ ($\simeq 2 \times 10^{-6}$) much lower than the rest of the sample but comparable to those inferred from the upper limits of other young pulsars. In the case of PSR B0906−49, the spectrum of the radio nebula is steeper than other radio PWN and the pulsar is the older than any other pulsar known to power a radio PWN. Clearly we need further broad-band studies of PWN produced under a variety of conditions to better understand how the radio emission from a PWN is produced and how it depends on the properties of its pulsar.

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Figure Captions

Fig. 1.— *Left:* VLA continuum image of the SNR G341.2+0.9 at λ20cm from Frail, Goss & Whiteoak (1994). The box indicates the extended radio emission surrounding PSR B1643-43. *Right and Top:* Greyscale and contour image of the region surrounding PSR B1643−43 at 1425 MHz. The plotted contours are 4.2, 4.5, 4.8, 5.1, 5.4, 5.7 and 6.0 mJy/beam. The beam size is 25″. The greyscale ranges from 4 to 5.8 mJy/beam. The cross indicates the position of the pulsar as derived in this paper. *Right and Bottom:* The same region at 4860 MHz. Contours are at levels of 0.16, 0.3, 0.4, 0.5, 0.7, 0.9 and 1.1 mJy/beam. The greyscale ranges from 0 to 1.3 mJy/beam. The cross indicates the position of the pulsar.

Fig. 2.— *Left and Top:* Greyscale and contour image of the region surrounding PSR B1706−44 at 1425 MHz. The plotted contours are 2.1, 2.25, 2.4, 2.55, 2.7, 3.0, 6.0 and 9.0 mJy/beam. The beam size is 25″. The greyscale goes linearly from 2.1 to 2.9 mJy/beam. The cross indicates the position of the pulsar as derived in this paper. *Right and Top:* The same region at 4860 MHz. The contours are 0.1, 0.3, 0.5, 0.7, 0.9, 1.1, 1.3 and 1.5 mJy/beam. The beam size is 25″. The greyscale ranges from 0 to 1 mJy/beam. The cross indicates the position of PSR B1706−44. *Bottom:* The same region around PSR B1706−44 at 8460 MHz. The contours level are 0.1, 0.3, 0.5, 0.65, 0.9 and 1.1 mJy/beam. The greyscale ranges from 0 to 0.7 mJy/beam. The cross indicates the position of the pulsar.

Table 1. Observational Parameters

Frequency [MHz]:	1425	4860	8460
VLA configuration:	BnA + CnB + DnC	CnB + DnC	CnB + DnC
Observing dates:	1997 Feb.7,8	1997 June 15	1997 June 16,17
	1993 June 2, 1997 June 13	1997 Oct.14	1997 Oct. 6,10
	1993 Oct. 14, 1997 Oct. 17		
Total observing time:	7+17.5+14 h	17.5+14 h	17.5+14h
Calibrators:	3C286, 1622-297	3C286, 1622-297	3C286, 1622-297
Synthesized beam [arcsec]:			
PSR B1643−43:	27×10	16×6	19.4×14
PSR B1706−44:	24 × 9	16×6	14 ×8
rms [mJy]:	0.04	0.04	0.04

Table 2. Observed parameters of the pulsar wind nebulae

Pulsar	ν (GHz)	S_{PSR} (mJy)	S_{PWN} (mJy)
B1643−43	1.42	1.0 ±0.2	31 ±13
	4.86	0.10 ±0.03	23 ±4
B1706−44	1.42	11.0 ±0.2	28±11
	4.86	2.0±0.7	28±6
	8.46	0.8 ±0.1	11±3

Note. — The columns are (left to right), (1) the pulsar's name, (2) frequency, (3) flux density of the pulsar, and (4) integrated flux density of the PWN.